ANALYSIS OF WATERCOURSE CHANGE DURING ALLUVIAL FAN FORMATION AND COUNTERMEASURE FOR STABILIZATION OF CHANNEL FLOW IN KARNALI RIVER, NEPAL

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ABSTRACT

In this study, we discussed watercourse changes during the alluvial fan formation of the Karnali River and proposed a countermeasure to stabilize the channel to maintain the ideal flow discharge in two branches. First, we observed and analyzed time series satellite images to understand the braided channel area of alluvial fan and major regions in which channel changes were occurring. Second, we conducted a numerical simulation to evaluate the water flow and sediment flow including river bed evolution numerically. The results demonstrated that the sediment deposited in the channels has narrowed the channels and deformed the bed, thereby raising the water level. As a result, the water has spread to adjacent areas, producing unstable channels and discharge instability in the two branches. Finally, we proposed countermeasures considering the major regions of change and those were in terms of discharge distribution, sediment deposition, and channel stability. This understanding of water course changes and the recommended countermeasures are helpful for managing rivers with braided channel alluvial fans.

Keywords: Alluvial fan, water course changes, sediment deposition, countermeasure, channel stabilization.

INTRODUCTION

Karnali River is longest river in Nepal. It originates from Tibet (China), passes through the Himalayan Mountains and plains of Nepal, and flows to India. The river has a catchment area of 43,000 km^2, and which includes snow-covered mountains. The slope of the river changes as it leaves the mountain: the single-channel river changes to braided channels, which flow into two channels: Karnali and Geruwa. The two channels join at approximately 44 km downstream in India, forming a large depositional landform of area about 789 km^2. (Rakhal, et al., 2021).

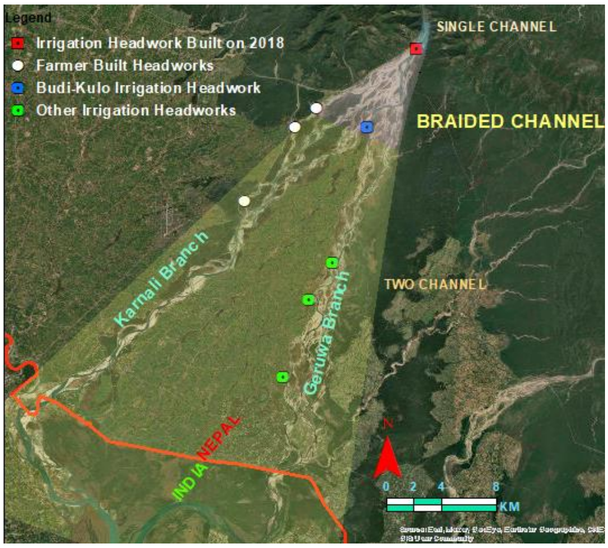

Figure 1: Map of Karnali Megafan (study area).

Temporal variation of discharge has been experienced in two branches. The local people describe the historical discharge of the Geruwa River branch as being approximately double that of

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the Karnali River branch during flood periods. Irrigation headworks were receiving water, and environmental flow was maintained in both branches. Farmers describes this flow condition as idealistic discharge in both branches. However, situation has reversed now. Due to the more recent river discharge shifting from the Geruwa to the Karnali River branch, the national park is experiencing environmental issues. Additionally, the small cities in the vicinity of the Karnali branch are experiencing embankment breaching and frequent flooding. The irrigation headworks located in the braided channel region are suffering from the effects of sedimentation; the irrigation headworks located along the Geruwa branch are suffering from a water intake deficit. So, determined land use pattern including human made structures like embankment and irrigation headworks in the vicinity of fan has suffered from the instability of discharge in two branches.

Distribution of discharge in two branch in this alluvial fan is affected from the changes of river courses in braided channel region of fan. Hence, Present study aims to understand the process of watercourse changes during the alluvial fan formation. Also aim to propose the countermeasure to stabilize the idealistic discharge in two branches. First, we observe and analyze the periodic satellite images to understand temporal change of watercourse. Second, we simulate the 2-D depth averaged numerical model to evaluate water flow and sediment flow including river bed evolution. Third, we propose the countermeasures for the stabilization of channels to maintain idealistic flow condition.

OBSERVATION AND ANALYSIS OF SATELLITE IMAGES

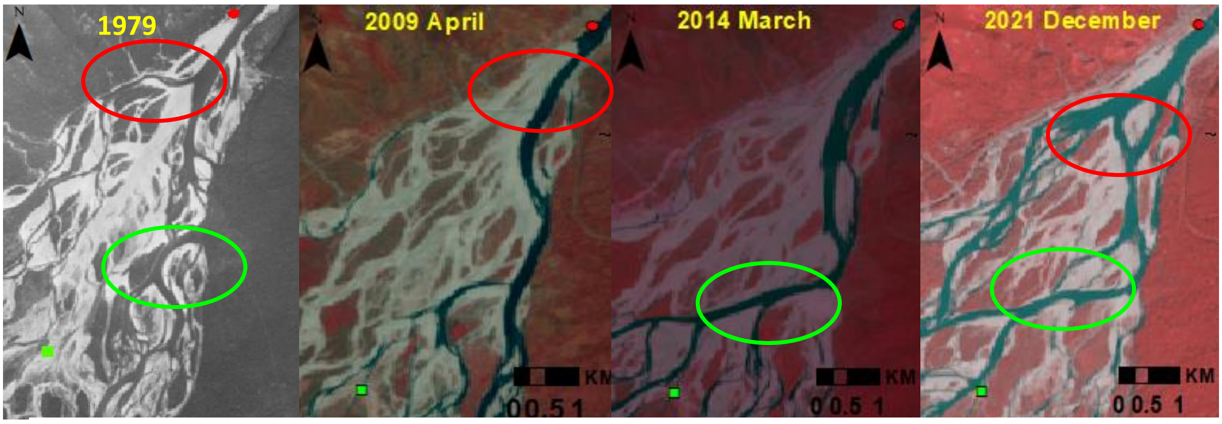

Figure 2: Satellite images showing temporal water course changes in the study region.

Water course changes in the braided channel area of the alluvial fan have affected the discharge of the two branches. Hence, we observed time series satellite images of the area, i.e., between the Rani-Jamara-Kulariya irrigation headwork (Figure 2, red dot) and the Budikulo irrigation headwork (Figure 2, green square) from 1972 to 2022. In this period, land has developed and eroded. Frequent water course changes occurred in the regions circled in red and green in Figure 2. Channel blockage and deposition continuously occurred as the water courses changed. The water courses in the green circled area changed throughout the period; the red circled area contained no prominent channel between 1979 to 2021. The major changes in these two regions resulted in unstable channels, and have affected the discharge distribution between the two branches. Currently, maintaining the ideal discharge distribution in both branches is important for maintaining channel stability. The flow in regions with frequently changing channels must be controlled. Hence, countermeasures need to be implemented in these regions to effectively stabilize the channels.

NUMERICAL EVALUTATION OF BRAIDED CHANNEL AREA

For our numerical simulation, we used a two-dimensional (2D) depth-averaged governing equation. We applied the mass and momentum conservation equation for water flow, mass conservation equations for suspended sediment and bed load, and erosion and deposition formulae.

For the bed load formula, we used the formula purposed by Egashira et al. (1997):

$$q_{b*} = \frac{4}{15}\frac{K_1^2 K_2}{\sqrt{f_d+f_f}}\tau_*^{5/2} \qquad (1)$$

where K_1, K_2, f_d, and f_f are theoretically specified.

We computed the erosion rate using the entrainment velocity (Harada et. al., 2022):

$$E = W_e C_s \qquad (2)$$

where W_e is the entrainment velocity, and C_s is the sediment concentration.

We calculated W_e by employing the following formula described by Egashira and Ashida (2019):

$$\frac{W_e}{v} = \frac{K}{R_{i*}}\ ,\ R_{i*} = \frac{\Delta\rho g h}{\rho v^2}\ , \mathrm{K}=1.5 \times 10^{-3} \qquad (3)$$

where v is the depth-averaged velocity, defined as $v = \sqrt{u^2 + v^2}$; R_{i*} is the overall Richardson number; $\Delta\rho$ is the density difference between the water and bed surface layers.

Computational Conditions

We prepared the computational domain in the Nyas2DH solver of iRIC. To understand the frequent changes in the bathymetry of the braided channel area and lacking periodic data, we used the Copernicus digital elevation model (DEM) with forests and buildings removed (FABDEM) for our simulation and discussion of countermeasures. FABDEM is global elevation model with a 30 m resolution built by Hawker et al. in 2022. Table 1 describes the calculation and domain information.

Table 1: Simulation calculation conditions.

Size of calculation domain	Length, 9.8 km; width, 400 m to 7.6 km
Number of rows and columns	301 × 136 = 40936
Calculation time step	0.1 s
Upstream discharge	Steady
Sediment type	Non uniform
Downstream condition	Uniform flow

RESULTS AND DISCUSSION

Verification

We conducted an 18-day simulation with a steady peak flood discharge of 17,900 m^3/s (60 -year return period). We compared the calculated results with the Landsat images. Figure 3 shows that the calculated sediment deposition pattern is similar to that observed in the Landsat images from 2021. On the seventh day of calculation, a sand bar formed in the middle of the channel (Figure 3, black circle) through sediment deposition, which we also observed in the Landsat image from December 2021.

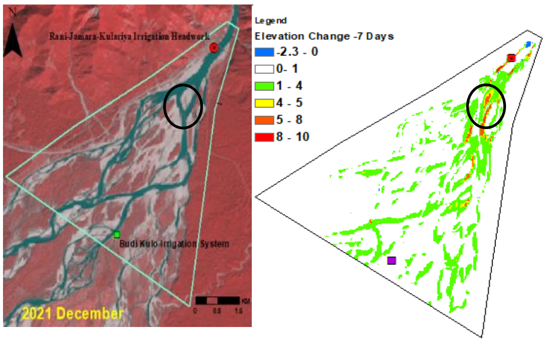

Figure 3: Verification of model.

Planform channel pattern

Figure 4 shows the comparison of plan form channel pattern changes in 18 days computation. Channel in initial period are relatively wide. 18 days channel are relatively narrow and more in numbers. Formation of new channel network with spreading of flow are observed.

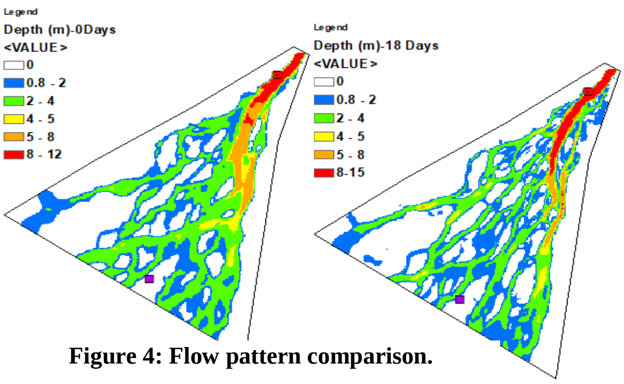

Figure 4: Flow pattern comparison.

Sediment depositional Characteristics

Figure 5 shows the sediment deposition characteristics in the study area. In the 18-day simulation, we observed sediment deposition up to 14 m. Sediment was deposited on the channel bed as well as the sides of the channel. We compared the form of the areas in which sediment was deposited, and found that sediment with a mean diameter of less than 5 mm was mainly deposited in the areas. We observed that deposition increased as mean sediment diameter reduced.

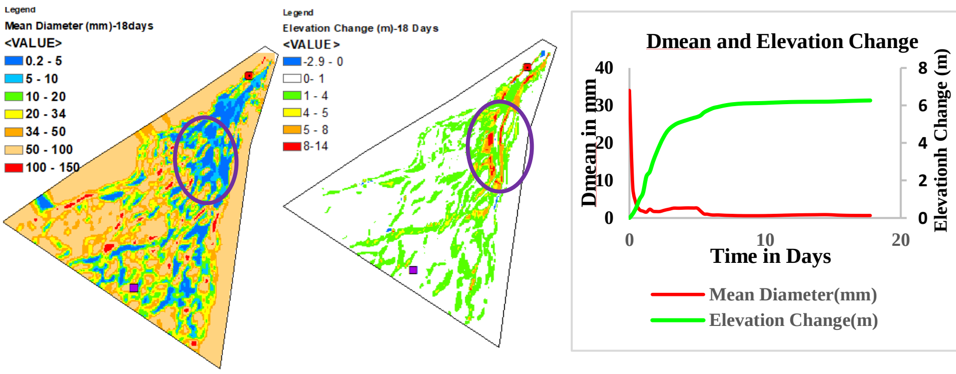

Figure 5: Comparison of sediment diameter and elevation change.

Sediment deposition and discharge distribution

Figure 6 illustrates how the bed deformation occurred in the section encircled in black. From initial to the seventh day in the computation, we observed a sand bar at the middle of the channel as well as deposition along the sides, which reduced the cross-sectional area of the main channel. With this deposition process, the water surface level in main channel raised and water spilled to the adjacent small channels, as shown in Figure 6. We observed that the sand bar moved from the middle to the right bank of the channel, and the bar size increased up to the 13th day of simulation. After this, we observed that the cross-sectional sand bar area decreased.

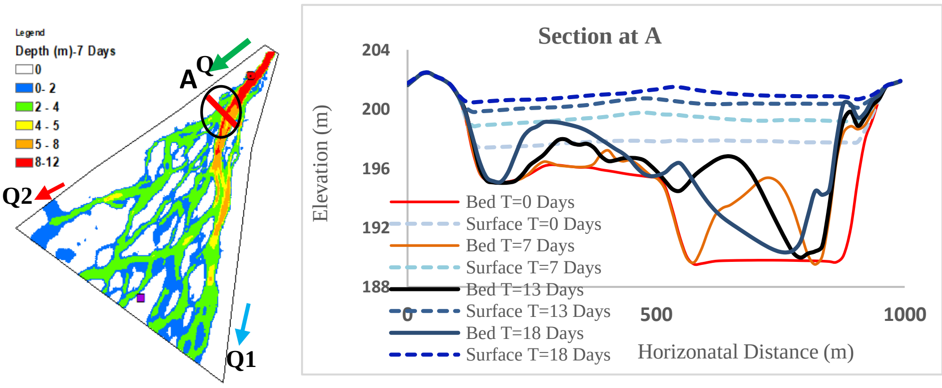

Figure 6: Temporal change in bed elevation at point A.

Figure 7 demonstrates the discharge distribution in the two branches. We observed frequent changes in the discharge in the two branches. In the 18 days of simulation, we observed four alternations in the discharge in the two branches. In Figure 7, the discharge changes in both branches and the bar formation (black circles area) in figure 6 can be linked with each other. From the 7th until the 13th day of simulation, the discharge of the Karnali branch increased, with a slight decrease on the 10th day. After the 13th day, the discharge of the Karnali branch abruptly fell, and we observed the opposite for the Geruwa branch. The bar size in the channel increased until the 13th day, which resulted in the decrease in the cross-sectional area of the main channel and an increase in the water level, leading to the river spilling into the adjacent channels that contributed to the Karnali branch. This flow process indicated discharge increases in the Karnali branch until the 13th day.

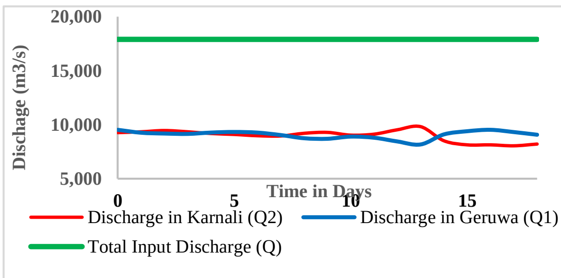

Figure 7: Discharge distribution in two branches

Then, as the bar size in the main channel decreased and the sediment deposition on the small adjacent channel increased, more flow entered the Geruwa branch. This process indicated how sediment deposition and erosion in some specific areas in this braided channel region of alluvial fan affect the channel discharge between the two branches.

CHANNEL STABILIZATION COUNTERMEASURES

To maintain the ideal flow conditions in the two branches, the channels must be stabilized. To achieve this goal, we developed countermeasures with an understanding of the frequent water course changes in the braided channel area of the alluvial plain, the present water and land use conditions, and the simulation results and analyses. Figure 7 shows a schematic diagram of the proposed countermeasures. We propose blocking the major contributors to the Karnali branch, i.e., channels 4, 5 and 6. Channel 3 should be left open to maintain the water head in the Budikulo irrigation headworks and environmental flow in the Karnali River. Such countermeasure might induce flow in the channel contributing to the Geruwa branch by reducing the sediment deposited in the main channel. We evaluated our simulation result and compared it with the without-countermeasure case in terms of discharge stability, sediment deposition, and flow pattern stability.

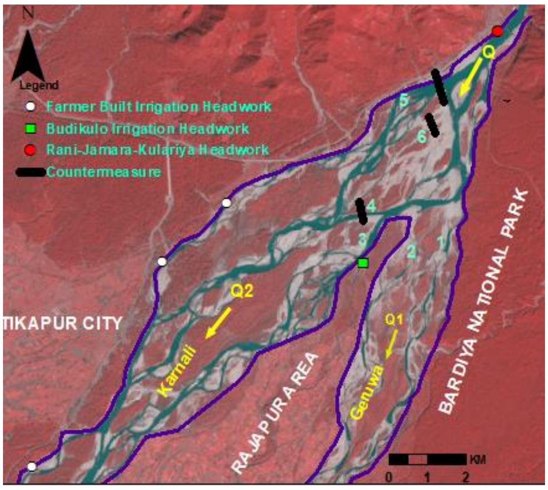

Figure 8: Proposed countermeasures.

We found that the flow pattern that formed on the 18th day of simulation with the implementation of countermeasures was comparatively wider and more stable. Figure 9 shows the sediment deposition in the braided channel region with and without countermeasures. In the without-countermeasure case, we observed sediment deposition up to 14 m along the sides of the channel, narrowing the channel and resulting in the spreading of flow. With the application of countermeasures, we observed deposition up to 11 m. Our observations of the sediment deposition demonstrated that the sediment deposition area reduced with the application of countermeasures, as shown by the dotted circle and dotted square. Figure 10 shows a comparison of the deposited sediment volume in the study area. The application of countermeasures reduces the suspended sediment deposition rate, and the deposition pattern is relatively stable. The implementation of the countermeasures reduces the sediment deposition by 13 million m^3 in the braided

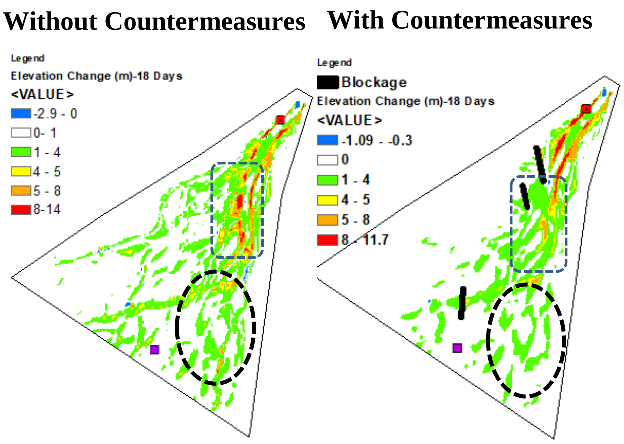

Figure 9: Comparison of sediment deposition height with and without countermeasures.

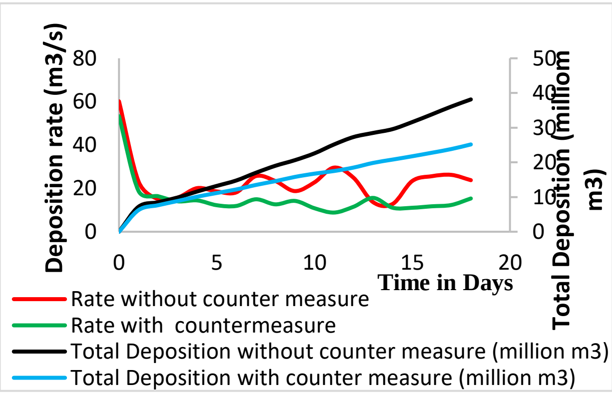

Figure 10: Suspended sediment deposition with and without countermeasures.

region, which is 34% less than the without applying countermeasures, helping to stabilize the channels and discharge. Figure 11 shows the discharge distribution of the two branches (Karnali (Q2) and Geruwa (Q1)) after the application of countermeasures. In the 18-day simulation, the discharge distribution relatively stabilized. We computed the minimum flow discharge ratio (Q1/Q2) in the 18 days as 1.7, and the flow pattern with the application of countermeasures indicated a permanent stable channel near the Budikulo irrigation headwork.

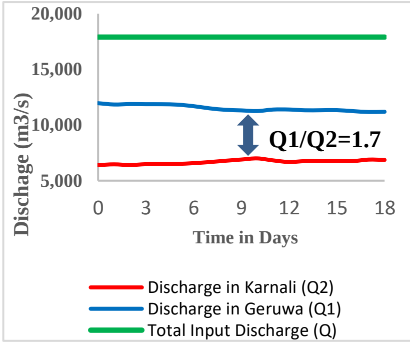

Figure 11: Discharge distribution among two branches with countermeasures.

CONCLUSIONS AND RECOMMENDATIONS

In this study, we discussed the changes in the watercourse of the two branches of the Karnali River that formed during the alluvial fan formation, which have affected the discharge distribution among the two branches. We observed and analyzed time series satellite images, and found sediment deposition and blocking of the channels, as well as the formation of new land forms and watercourse changes. Our computational results from a numerical simulation showed the sediment deposition characteristics of the region and the instability of channel, which result in unstable discharge in the two branches. Considering the historic satellite images, the simulation results, and local land and water use conditions, we proposed countermeasures to maintain the ideal discharge that matches present water use and land use conditions. We evaluated these countermeasures in terms of channel stability, sediment deposition, and discharge distribution among the two branches. We observed relatively wide and stable channels with concentrated flow in the countermeasure case. We found that sediment deposition in the study area reduced by 34% in our 18-day simulation with the application of countermeasures. By reducing the sediment deposition in the braided channel area, stable channels can be obtained to maintain a relatively stable discharge distribution in the two branches with a Q1/Q2 ratio of 1.7.

Our findings provide information about the changes in the watercourse in the alluvial fan of the Karnali River, which result in frequent changes in the discharge of the two branches. We provided suggestions for the management of these braided channels to mitigate the occurrences of flooding in the downstream areas. We conducted this study with limited bathymetry and sediment data of the study area. Upstream sediment supply information was also limited. In future studies, researchers may examined the effects of changes in the sediment supply due to earthquakes on the braided channel morphology. The continuously changing bathymetry in the region necessitates periodic measurements, so such measurements are required for future research and analyses.

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